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## SILICA GLASS CRUCIBLE

### BACKGROUND OF THE INVENTION

The present invention is related to the field of silica crucibles, and more  
5 specifically to a silica crucible having a multi-layer wall in which one or more of the  
wall layers are doped with aluminum.

Silicon wafers used in semiconductor industries are made from ingots of  
single-crystal silicon. Such ingots generally are manufactured by one of two  
processes: the Czochralski (CZ) process and the floating zone (FZ) process.  
10 Among those, the CZ-process is more widely used for mass production of single-  
crystal ingots.

In the CZ-process, metallic silicon is charged in a silica glass crucible housed  
within a susceptor located in a crystal growth chamber. The charge is then heated  
by a heater surrounding the susceptor to melt the charged silicon. The susceptor  
15 typically is rotated during this procedure. A single silicon crystal is pulled from the  
silicon melt at or near the melting temperature of silicon.

For higher ingot productivity, a more rapid CZ-process is desirable.  
However, accelerating the crystal pulling rate beyond a certain rate results in  
improper silicon crystal structures. Many trials are done to shorten the "melt down"  
20 period by increasing heating power. Similarly, in the production of large-diameter  
wafers, the amount of silicon charge and the melt-down time are increased and more  
intense energy is input. The total process time is much longer than that for small-  
diameter ingots.

This harsh melt-down procedure increases the rate of crucible inner surface roughening. Compressing the meltdown period also negatively affects the rigidity of silica crucible. Silica glass is not hard enough to prevent sagging of the side wall in harsher melt down processes. A more dimensionally stable crucible is desired.

5        At operating temperatures, the inner surface of a silica crucible reacts with the silicon melt. In many cases, it is the inner layer of the crucible that undergoes a change in morphology. More exactly, the inner surface roughens after prolonged operation in the CZ-process. This roughening can cause a loss of crystal structure of the pulled ingot. Inner surface roughening renders the crucible unfit for use in  
10    silicon ingot manufacture.

Additionally, the inner layer of a silica glass crucible can be dissolved into the silicon melt during the CZ-process. Silicon and oxygen, the main components of a silica crucible, are not deleterious to the silicon melt. However, impurities in the inner layer of the crucible can be transferred to the silicon melt during this process.

15    To keep the silicon melt free from such impurities, a crucible is required to be extremely pure or to be insoluble by the silicon melt.

A standard method for making a silica glass crucible is disclosed in U.S. Patent No. 4,935,046. Quartz grain is supplied in a rotating mold in a crucible shape. The grain is then heated by an electric arc to fuse the inner part of the formed  
20    grain, leaving the outside grain unfused. During fusion, additional grain is supplied to the inside surface of the crucible. Quartz grain is melted and piled up as a transparent inner layer, while the formed grain is fused rather promptly to make an translucent silica glass substrate. The resultant crucible has a wall comprising a

transparent inner layer and an translucent outer layer having a rough outer surface, which is the interface between fused grain and unfused grain.

One crucible is known to reduce the dissolution of the inner surface of the crucible. U.S. Patent Nos. 5,976,247 and 5,980,629 disclose the creation of a  
5 “devitrified” layer inside of a crucible to prevent particulate generation at the silica-melt interface. The devitrified layer is reported to dissolve uniformly. Here, the devitrified layer means a crystallized silica layer, which the present inventors found to dissolve more slowly in the silicon melt than does amorphous silica. The above references claim alkaline-earth elements as a devitrification promoter, with barium  
10 recited as an example.

One of the present inventors filed Japanese Patent 3100836 (laid open Tokukai Hei8-2932), teaching an inner layer containing from 100–2000ppm aluminum and 0.5–1mm in thickness. The inner layer crystallizes in the CZ-process, so dissolution is suppressed and the dimensional stability of the crucible is  
15 improved.

It is known in the ingot manufacturing industry that circular patterns (“rosettes”) are observed on the crucible surface contacting the silicon melt. Examples are shown in U.S. Patent No. 4,935,046, figures 6A-6B. The ring is referred to in U.S. Patent No. 4,935,046 as crystobalite. This phenomenon was  
20 investigated and determined to be a rosette surrounded by crystobalite.

The crystobalite ring is normally decorated with brown deposit when cooled down after a CZ-process use. It is hypothesized that the brown deposit is either silicon mono-oxide or colloidal silicon. The center of the rosette has a rough surface that is either not covered by crystobalite or covered by a very thin crystobalite layer.

The outside of the rosette is the original silica glass surface, which has retained its original smoothness.

As CZ-process time continues, rosettes grow and the surfaces of the rosette centers become rough. Further, the rosettes merge and the rough surface area is increased. The smooth virgin surface decreases and finally disappears. When a major portion of the inner surface of the crucible is covered by a rough surface, the pulled silicon crystal loses its crystalline structure. Such a roughened crucible is unsuitable for ingot manufacture and silicon crystal pulling using a roughened crucible must be ceased to avoid manufacture of substandard ingots.

A method to reduce roughening of the crucible inner surface is disclosed in U.S. Patent No. 4,935,046. The reference further mentions that growth of cristobalite is suppressed, as the result of applying the method. By applying the layer-by-layer deposition method as taught by this reference, however, suppression of cristobalite is insufficient and roughening still proceeds to a significant extent.

“Devitrification” of the outer layer of a crucible is disclosed in U.S. Patent Nos. 5,976,247 and 5,980,629. By coating a crucible with barium-containing chemicals, the outside of the crucible is “devitrified”, i.e., crystallized, when used in a CZ-process. This crystallized layer reinforces the crucible at operating temperatures and prevents sagging of the crucible side wall.

By using barium as a crystallization promoter, the crystallized layer grows as CZ-process time elapses. The silica glass experiences a large volume change when it crystallizes, creating stress at each of the interfaces of the glassy phase and crystalline phase. This stress is relieved by micro-scale deformation of the crucible. If the crystalline layer thickness exceeds a certain level, the crucible is prone to

cracks and possible leakage of the silicon melt. Even if the amount of barium-doped material is carefully optimized to the running conditions, the crucible nevertheless occasionally experiences cracking toward the end of a CZ-process run.

Japanese Patent P2000-247778A discloses a three-layer crucible. The layers  
5 are a transparent synthetic silica inner layer, a synthetic silica or natural quartz glass middle layer, and an aluminum-doped silica outer layer. The optimum range for aluminum concentration in the outer layer is reported to be 50–120ppm. The best mode taught in this reference has an approximately 3mm thick outer layer doped with aluminum at about 75ppm.

10 The doped aluminum outer layer helps to prevent sagging of crucible. However, the inner layer of this crucible is still prone to uncontrolled rosette formation and growth during a CZ-process.

A long-life crucible is therefore desirable, especially a large-diameter CZ-process crucible. Specifically, the side wall of the crucible should be able to  
15 maintain its structural integrity without warping, and the inner surface of the wall should resist roughening during a CZ-process.

## SUMMARY OF THE INVENTION

Generally, the present invention provides a silica glass crucible comprising a  
20 wall, including a bottom wall and a side wall, and an aluminum-doped layer formed on the inner portion of the wall. In a preferred embodiment, an aluminum-doped layer is also formed on an outer portion of the side wall.

The silica glass crucible according to this aspect of the invention is made by introducing into a rotating crucible mold bulk silica grain, consisting essentially of

quartz grain, to form a bulky wall including a bottom wall and a side wall. After heating the interior of the mold to fuse the bulk silica grains, an inner silica grain, doped with aluminum, is introduced into the mold. The heat also at least partially melts the inner silica grain, allowing it to fuse to the wall to form an inner layer.

5 The crucible, thus fused, is then cooled. Optionally, the crucible can be held at a high temperature to form a plurality of nuclei of crystalline silica within the inner layer. In the preferred embodiment described above, outer silica grain doped with aluminum is introduced into the rotating mold to form an outer layer prior to introduction of the bulk grain.

10 Another aspect of the invention is a silica glass crucible having a wall, wherein a layer formed on an inner portion of the wall is non-homogeneously doped with aluminum to promote crystallization of silica. A method for making a silica glass crucible according to this embodiment is similar to that described above, however, the inner silica grain employed to produce this embodiment is a non-  
15 homogeneous combination of silica grain containing aluminum. The non-homogeneous combination of silica grain can be a mixture of aluminum-doped and aluminum-free silica grains. Alternatively, aluminum-coated coarse quartz grain can be utilized.

The invention will become more readily apparent from the following  
20 Detailed Description, which proceeds with reference to the drawings, in which:

## **BRIEF DESCRIPTION OF THE DRAWINGS**

**FIG. 1** is a cross-sectional view of one embodiment of a silica glass crucible according to the present invention.

**FIG. 2** is an enlarged, partial cross-sectional view of the side portion of the wall of the silica glass crucible shown in **FIG. 1**.

**FIG. 3** is an enlarged, partial cross-sectional view of the bottom portion of the wall of the silica glass crucible shown in **FIG. 1**.

5       **FIGS. 4–7** are cross-sectional views of methods for making alternative embodiment silica glass crucibles according to the present invention.

**FIGS. 8–10** are partial plan views of an inner surface of a silica glass crucible of the prior art, showing silica crystallization rosettes occurring during a CZ-process.

10       **FIG. 11** is a partial, enlarged top view of the prior art crucible wall shown in **FIG. 8**, illustrating the structure of a silica crystallization rosette.

**FIG. 12** is a cross-sectional view of the prior art crucible inner surface and silica crystallization rosette depicted in **FIG. 11**.

15       **FIGS. 13–15** are partial plan views of an inner surface of a silica glass crucible according to one embodiment of the present invention, showing silica crystallization occurring during a CZ-process.

**FIG. 16** is a partial, enlarged top view of present invention crucible inner surface shown in **FIG. 13**, illustrating the structure of a silica crystallization rosette.

20       **FIG. 17** is a cross-sectional view of the crucible wall and silica crystallization rosette depicted in **FIG. 16**.

**FIG. 18** is a partial, enlarged top view of a present invention crucible inner surface, showing an alternative silica crystallization rosette wherein the crystallization front is proceeding ahead of the ring.

**FIG. 19** is a cross-sectional view of the crucible wall and alternative silica crystallization rosette depicted in **FIG. 18**.

**FIG. 20** is an enlarged, partial cross-sectional view of the wall of the silica glass crucible shown in **FIG. 1** in an embodiment wherein the crucible was held at  
5 high temperature to promote crystallization of silica within the inner surface.

**TABLES 1-2** list construction and performance parameters of four exemplary crucibles of the present invention and one prior art crucible.

#### **DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT(S)**

10 In more detail, one aspect of the present invention provides a silica glass crucible suitable for use in a CZ-process. Turning now to **FIG. 1**, one aspect of the present invention is a silica glass crucible **1** having a wall **10** defining an interior cavity **12**. The wall **10** comprises a side wall **10s** (**FIG. 2**) and a bottom wall **10b** (**FIG. 3**).

15 The side wall **10s** comprises a bulk layer **14** of pure silica. The bulk layer **14** generally is not doped with aluminum. A layer **16** can be formed on the inner portion of the wall **10**. The inner layer **16** is comprised of fused silica grain homogeneously doped with aluminum in the range of 50–500ppm, preferably 80–160ppm, and most preferably 100–120ppm.

20 In the alternative embodiment of the crucible shown in **FIGS. 1–3**, an aluminum-doped layer is also formed on the outer portion of the wall **10**. The outer layer **18** is approximately 0.5–2.5mm in thickness and can be doped with aluminum in the range of about 100–500ppm. In a preferred embodiment, the outer layer **18** is doped with aluminum in the range of about 120–500ppm.



An enlarged view of a side portion of the wall of the above alternative embodiment is shown in cross-section in **FIG. 2**. The side wall **10s** comprises the bulk layer **14**, the inner layer **16** and the outer layer **18**. In a representative crucible, the side wall **10s** has a thickness of approximately 8.0mm, of which the inner layer

5    **16** comprises 0.2–1.2mm, the outer layer **18** comprises 0.5–2.5mm, and the bulk layer **14** constitutes the remaining 4.3–7.3mm.

An enlarged view of the bottom wall of the crucible of **FIG. 1** is shown in cross-section in **FIG. 3**. Consistent with the representative example discussed above, the bottom wall **10b** typically has a total thickness of 10.0mm, of which

10    approximately 0.2–1.2mm comprises an inner layer **16**. The bottom wall **10b** of the crucible of this embodiment can alternatively be constructed with an aluminum-doped outer layer (not shown).

Another aspect of the present invention is a method to make such crucibles. The method shown in **FIGS. 4–6** is for making the alternative embodiment of the

15    invention having both an inner layer and an outer layer. The formation of an outer grain layer **32** in the crucible wall **10** need not be performed to produce a crucible having an aluminum-doped inner layer **16** but not a doped outer layer **18**. For illustrative convenience, these figures show a grain introduction apparatus having multiple metered grain hoppers.

20    An outer grain layer of a three-layer crucible is formed in a rotating mold **20**, as shown in **FIG. 4**. An outer grain hopper **22a** communicates via a feed tube **24** with the interior of the mold **20**. The feed tube **24** can employ a valve **26a** to meter the flow of silica grain **30** from the hopper **22a** to the interior of the mold **20**. Outer silica grain **30** is flowed thereby into the rotating mold **20**. Rotation of the crucible

mold **20** provides sufficient centrifugal force to retain the poured outer silica grain **30** on the inner side surface of the mold **20** as outer grain layer **32**.

To form the bulk grain layer **36**, the bulk hopper **22b**, grain flow meter **26b** and feed tube **24** are used. In **FIG. 5**, bulk silica grain **34** is introduced into the mold **20** to form the bulk grain layer **36**. The bulk silica grain **34** is preferably pure quartz grain.

When constructing a crucible having an outer layer **18**, it is possible to vary or decrease the speed of rotation of the mold **20** to permit the bulk silica grain **34** to be applied to the side and bottom of the mold. Thus, outer silica grain **30** can be deposited on the sides and bottom of the mold **20**, to produce a crucible **1** wherein the outer layer **18** comprises both the side wall **10s** and bottom wall **10b**.

A spatula (not shown), shaped to conform to the inner surface of the mold, is generally used to shape the introduced outer and/or bulk silica grain. In this manner, the outer grain layer **32** and bulk grain layer **36** each can be formed to a selected thickness.

Fusion of formed silica grain is shown in **FIG. 6**. An electrode assembly, comprising a power source **36** and electrodes **38a,38b**, is positioned partially within the interior cavity of the rotating mold **20**. An electric arc is produced between electrodes **38a,38b** by supplying 250–350V and approximately 1800A direct current. A region of heat **42** is thereby generated within the mold interior. This heat **42** serves to fuse formed grain layers **30,34** in the mold.

Fusion proceeds through the formed grain from proximal to distal, relative to electrodes **38a,38b**. The mechanism of progressive fusion through the silica grain layer according to this technique is known to those skilled in the art.

After fusion of the surface of the formed bulk grain layer 36, inner silica grain 44 is poured from the inner silica grain hopper 22c through feed tube 40; flow regulating valve 26c can be utilized similarly to valves 26a,26b. The rate of inner silica grain 44 deposition is controlled via the introduction rate of inner silica grain

5 44. An exemplary manufacture according to this method introduces inner silica grain 44 into the mold 20 at 130 grams/minute for three minutes. The arc produced between the electrodes 38a,38b creates a very strong plasma field, propelling the partially melted inner silica grain 44 outward, enabling it to be deposited on the sides and bottom of the crucible inner surface.

10 The inner grain 44 passes through the heated region 42, is at least partially melted by the arc flame therein, and is deposited on the surface of the bulk grain layer 36. The inner grain 44 thus deposited is fused to the bulk grain layer 36 to form an inner layer 16. Molten inner grain 44 thereby is continuously deposited and fused over a period of time of inner layer formation. The inner layer 16 thus formed

15 is essentially transparent and bubble-free.

Conversely, the process results in outer layer 18 and bulk layer 14 (FIG. 1), when present by forming the outer grain layer 32 and bulk grain layer 36, respectively, and subsequently fusing them, as described. After fusion, these layers 18,14 typically are translucent and contain numerous tiny bubbles.

20 Fusion is carried out so that unfused grain is preserved between the mold 20 and fused bulk layer 14 (or outer layer 18, if present) of the side wall 10s. Unfused bulk silica grain 34 is left at the bottom 10b and side wall 10s. Thus, a rough, bubble-containing outermost surface results. For this reason, the thickness of an outer grain layer formed prior to fusion does not control the final depth of an outer

layer. Rather, it is the degree to which fusion is carried on that will determine the final outer layer depth.

After formation of the inner layer 16 by the deposition and fusion step discussed above, the crucible is cooled forthwith. A minimum cooling time, e.g. approximately 90 seconds, is necessary before a crucible thus manufactured has sufficient structural rigidity to permit removal from the mold 20 without deformation.

Optionally, the crucible can be held at a selected temperature for a selected period of time, or the crucible can be cooled at a controlled rate. Cooling times, temperatures and effects are discussed with reference to specific examples, below. Final processing can include fine sanding or polishing of the crucible exterior surface, edge cutting, cleaning and packaging to protect the crucible.

The inner layer 16 in the wall 10 of a crucible of the present invention is doped homogeneously with aluminum in the range of about 50–500ppm, and most preferably between 100–120ppm. The inner layer 16 should be free of bubbles, as a bubble entrapped within the inner layer 16 may serve as an initiation point of cracking of the layer when crystallized.

Aluminum is chosen as the doping component, because its use permits silica crystallization to be limited to the doped layer of the crucible wall 10. The range of aluminum doping was found to be effective in the crucible of the present invention to provide structural integrity without inducing cracking.

This crystallization is particularly important where the silicon melt contacts the inner surface of the crucible. A crucible made with an homogeneous doping level below about 50ppm fails to achieve the desired partial silica crystallization of

the relevant inner layer 16 during the time period of a typical CZ-process.

Conversely, only marginal additional benefit is gained by raising the aluminum doping level in the inner layer 16 above about 500ppm.

The inner layer 16 in the wall 10 of this crucible further has a depth of about  
5 0.2–1.2mm, and preferably 0.3–0.7mm. An experimental crucible having an  
aluminum-doped inner layer 16 greater than about 1.2mm deep experiences cracking  
during a CZ-process. This cracking is believed to be the result of stress at the  
junctions of the crystalline and glassy silica phases within the wall 10.

The inner layer 16 must possess a threshold depth in order to promote silica  
10 crystallization within the layer. A doped inner layer 16 less than about 0.2mm deep  
exhibits incomplete silica crystallization when used in an exemplary CZ-process  
application.

An alternative embodiment of the crucible thus described further comprises  
an aluminum-doped outer layer 18 in the wall 10. The outer layer 18 of such a  
15 crucible is doped with aluminum in the range of about 100–500ppm, preferably  
120–500ppm. Doping at levels above 500ppm imparts no further advantage to the  
crucible of the present invention. Similarly, uniform crystallization of the outer  
layer 18 is not observed when the outer layer is doped below about 100ppm.

The outer layer of the bottom wall 10b is preferably not doped. The bottom  
20 wall 10b should not sag down, because it is supported by the susceptor. There is  
normally a small gap between the exterior surface of the bottom of the crucible and  
the susceptor. This gap is eliminated during silicon melt-down by deformation of  
the crucible in response to the heat applied to the crucible. Aluminum doping to this  
bottom wall 10b actually may suppress this conformation process.

The outer layer **18** in the wall **10** of the above crucible has a depth of about 0.5–2.5mm. An outer layer **18** depth less than about 0.5mm results in silica crystallization that is not uniform. Cracking is observed at the junction of the bottom wall **10b** and side wall **110** in a crucible having a doped outer layer greater than about 2.5mm deep. The outer layer **18** therefore can be made to greater depths than the inner layer **16** and yet resist cracking. The tolerance of the outer layer as to maximum depth is attributed to the numerous bubbles resident within the outer layer, coupled with the rough outer surface. These microstructures of the outer layer seem to allow a thicker crystallized layer without cracking.

In another alternative embodiment, a crucible inner layer **16** is non-homogeneously doped with aluminum. This crucible is made according to the steps set forth above in **FIGS. 4-5**. **FIG. 7** shows the non-homogeneously aluminum-doped silica grain **47,48** that replaces inner silica grain **44**.

As shown in **FIG. 7**, a two-hopper system can be employed wherein aluminum-doped inner grain **47** is introduced from a hopper **22c** and non-doped quartz inner grain **48** is introduced from a second hopper **22d**. As an alternative, the mixture of grains **47,48** can be pre-mixed and delivered from a single hopper **22c**.

The hoppers can have stirring means **28c,28d** to maintain uniformity of the silica grain housed in the hoppers. Metering means **26c,26d** can be utilized to regulate the rates of grain introduction in the same fashion as has been previously described.

A representative mixture comprises aluminum-doped silica grain **47**, e.g., 160ppm aluminum-doped, mixed with non-doped silica grain **48**. The non-doped silica grain **48** can be natural quartz, which inherently and uniformly is contaminated

with aluminum, generally at levels less than about 18ppm. Alternatively, the present invention can use synthetic silica grain, typically containing less than 1ppm aluminum. The two grains **47,48** are preferably combined at an approximately 1:1 ratio to maximize the non-homogeneity of the mixture, although other doping levels and ratios are efficacious.

Non-homogeneous doping of aluminum is in the range of about 30–100ppm as an average aluminum concentration in an inner layer **16**, and preferably less than 80ppm on average. The method of mixing, or blending, aluminum-doped silica grain and non-doped silica grain is preferable for producing a crucible with an inner layer **16** doped with aluminum in the range of 30–80ppm. Synthetic silica grain can be used in place of pure (non-doped) natural silica grain to produce an inner layer **16** having an average doping level of less than about 50ppm.

In this embodiment of the invention, mixing of aluminum-doped grain **47** and pure silica grain **48** can be done as a separate process prior to the mixture's introduction in crucible manufacture. In this case, the pre-mixed grain **47,48** is placed in one hopper and can be introduced using a metering valve, similar to the method shown in **FIG. 6**.

In an alternative embodiment of this aspect of the invention, non-homogeneously aluminum-doped inner silica grain can be comprised of aluminum-coated coarse silica grain. Employment of coated coarse silica grain is preferable where the desired inner layer doping level is in the range of 80–100ppm as an inner layer **16** average aluminum concentration.

To be denominated “coarse grain”, the grain preferably contains silica grains of sizes larger than and smaller than 200 $\mu$ m. At least one-fifth of the grains in the

coarse grain described herein should have a size greater than  $200\mu\text{m}$ . In a preferred embodiment, approximately half of the grains in the coarse grain are larger than  $200\mu\text{m}$ .

Aluminum coating can be accomplished by any means creating aluminum-containing film on the silica grain. The preferable film is a layer of aluminum oxide or alumina. One method of achieving an aluminum film is to wet the silica grain with aqueous aluminum nitrate solution ( $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ ), then tumble dry in a rotary kiln. Other inorganic or organic aluminum compounds can be employed in place of aluminum nitrate, e.g.,  $\text{Al}(\text{OH})_3$ ,  $\text{AlCl}_3$ , or  $\text{Al}(\text{HCO}_2)_3$ .

As discussed earlier, rosettes form on the inner surface of a crucible during a CZ-process (**FIGS. 8-10**). **FIG. 8** depicts an inner surface **50** of a crucible, on which have formed a plurality of rosettes where the crucible surface **50** contacts the silicon melt. A rosette generally has a ring **52**; the ring and the region inside the ring are cristobalite **56**.

During a CZ-process, the rosettes grow in area, spreading to cover an increasing percentage of the inner layer surface **50**, as shown in **FIG. 9**. As the rosette grows, a rough texture **54** appears in the center. The rough surface area **54** within the boundaries of the rosettes also expands across the crucible inner surface. **FIG. 10** shows the state of an exemplary crucible inner surface **50** of the prior art later in the CZ-process. Rosettes merge and the rough surface area **54** is increased. As discussed above, inner surface roughening adversely impacts the crystalline structure of the growing silicon ingot.

Enlarged top and cross-sectional views of a rosette of the prior art are shown in **FIGS. 11-12**. The center of the rosette has a rough surface texture **54** surrounded



by cristobalite (crystalline silica) 56, the latter of which is seen to extend partway into the crucible wall 10 from the inner surface 50. The cristobalite ring 52 is decorated with brown materials and normally is observed as a brown ring on the inner surface of a used crucible. In some rosettes of the prior art, a small smooth surface boundary 55 exists between the rough area 54 and the inner edge of the ring 52.

Regarding these rosettes and concomitant surface roughening, the present invention employs aluminum doping to provide three modes for lengthening the useful life of a crucible suitable for use in a CZ-process. First, generation of rosettes can be suppressed by crystallizing the inner surface of a crucible wall (FIG. 20) prior to silicon charge melt-down in a CZ-process. This is accomplished by controlling the cooling step of the method of the present invention. A crucible cooled down rather slowly in the mold, or held at sufficient temperature, resists rosette formation via this mode.

In this mode, the inner surface of the crucible is covered with cristobalite before melt-down of the charged silicon. Rosettes are not formed by a reaction between the silicon melt and crystalline silica. Because a rosette is not generated, a rough surface area does not appear and the inner surface remains smooth.

Some silicon ingot manufacturers perform multiple silicon crystal "pulls" during a single CZ-process. In these uses, a portion of the crucible side wall is alternately covered by the melt, exposed to atmosphere as the melt level drops, then covered again as silicon charge is added to begin another ingot pull. The inner surface of a crucible thus used is subjected to high stress for a longer time period, making more important the inner surface textural integrity.

The fully crystallized mode is difficult to produce if the aluminum is doped uniformly throughout the inner layer 16. By non-homogeneously doping, a fully crystallized inner layer 16 can be formed readily with average doping levels below 100ppm. Also, the depth of the doping within the inner layer 16 has a direct effect  
5 on the rapidity of crystallization in the layer. Therefore, the depth of aluminum doping in the inner layer 16 is important to achieve a fully crystallized inner layer during crucible manufacture.

A second mode of maintaining crucible usefulness is to prevent generation of the rough area 54 in the growing rosette. Rosettes initially form as on the inner  
10 surface of a crucible according to the present invention (**FIG. 13**) similarly to those formed on walls of prior art a crucible (**FIG. 8**). In the present invention crucible, the inner surface of the rosettes that form on the inner surface 60 retain a smooth texture 62. Rosettes continue to grow and merge as occurs on prior art crucible inner surfaces 50, but the smooth surface 62 persists on the inner surface 60 of the  
15 present invention crucible (**FIGS. 14-15**).

**FIGS. 16-17** show a plan view and an enlarged cross-sectional view of a rosette growing on the inner surface 62 of the present invention crucible operating in this mode. This rosette comprises a ring 52 at the outer boundary of the rosette, within which is found cristobalite 56. The cristobalite 56 extends into the inner  
20 layer 16 of the crucible wall 10. In contrast to the crucible inner surface 50 of the prior art, the present invention retains a smooth surface 62 within the ring 52 and rosette.

The third mode of maintaining a smooth crucible inner surface is to stifle growth of the rosettes 52, as shown in **FIGS. 18-19**. The ring 52 of a rosette is

crystobalite, which may act as a nucleation site to grow crystalline silica 56 in the silica glass of the inner layer 16. In the example rosette shown in FIGS. 18-19, a corona of crystobalite grows faster than growth of the crystobalite ring 52, such that the ring 52 is surrounded by crystalline silica 56. When the ring 52 is bounded by crystalline silica 56, it is observed that the growth rate of the rosette is decreased by at least 50%.

The original inner surface 60 remains smooth glass. This surface 60 does not degrade as rapidly as in the prior art (FIGS 9-10). The combination of a large smooth surface 60 and slow-growing smooth crystobalite surface 56 work to maintain a smooth crucible inner surface during a prolonged CZ-process.

The present invention permits selection among these three modes to suit the particular application desired. The rate of crystobalite growth is fastest in the first mode, then the third, and lastly the second. More rapid crystobalite formation and growth is achieved by slower cooling in crucible production compared to traditional cooling. Higher aluminum doping levels enhance the crystobalite growth rate, as does a thinner inner layer. Faster crystobalite growth results with non-homogeneous doping, and especially with non-homogeneous doping using a mixture comprising synthetic silica grain rather than coated coarse silica grain.

Crucible design should preferably be tuned to the conditions of the contemplated CZ-process, and specifically to the heating schedule. An application desirous of a pre-crystallized inner surface (mode 1) would be production of silicon crystals for use in solar cells. Such manufacture typically involves a fast, harsh melt-down of the silicon charge, providing little time for the inner surface to crystallize. Conversely, manufacture of highest-quality ingots for semiconductor

use generally employs a slower melt-down and longer processing time. A crucible operating in mode 3 is best suited to this process.

By using aluminum as a crystallization promoter, the thickness of the crystallization in the layer is controlled. Only the region doped with aluminum  
5 crystallizes; regions not doped with aluminum do not crystallize during a typical CZ-process operation. This characteristic gives a crucible designer greater freedom to tailor the crucible to the needs of the process in which it will be employed.

The three modes of inner surface smoothness preservation are difficult to achieve if the inner layer doping is uniform and the amount of homogeneous doping  
10 is lower than about 50ppm. Employment of non-homogeneous aluminum doping enables control of silica crystallization in the inner layer and the use of lower aluminum doping levels. A combination of a lesser doping amount, e.g. less than about 100ppm, and distributing the aluminum doping non-homogeneously throughout the inner layer 16 provides the greatest benefit, especially when non-  
15 homogeneous doping is performed by blending with synthetic silica grain. The lifetime of a crucible made in accordance with the present invention thereby is improved.

#### Examples

Four crucibles A, B, C and D of the present invention were manufactured to  
20 similar dimensions. As well, crucible P was constructed according to the prior art. The nominal diameter of each crucible was 22 inches.

The inner layer 16 of Crucible A was made using non-homogeneously aluminum-doped inner silica grain mixture. Doped inner silica grain 47, doped to a level of 105ppm, was mixed with pure inner silica grain 48, having a natural

aluminum content of about 8ppm. The two inner silica grains **47,48** were mixed in a ratio of 54:46, yielding an average aluminum content in the inner layer **16** of 60ppm.

Crucible **B** likewise was made with a non-homogeneously doped inner layer **16**. The mixture used to construct the inner layer **16** of this crucible was 105ppm aluminum-doped inner silica grain **47** and pure synthetic silica grain **48**, the latter containing less than 0.5ppm aluminum. The doped and pure inner silica grains **47,48** were mixed in a 1:2 ratio, resulting in an average aluminum content of 35ppm for this mixture.

The non-homogeneously aluminum-doped inner layer **16** of Crucible **C** was manufactured using aluminum-coated coarse natural silica grain. The average aluminum content of this inner grain was 85ppm and 42% of the grains were larger than 200 $\mu$ m in size.

Crucibles **A–C** were made according to the above-disclosed method for making a crucible having a non-homogeneously aluminum-doped inner layer **16**. The three crucibles were cooled in the mold **20** for five minutes before removal and final processing.

The prior art crucible, Crucible **P** is of 22-inch diameter. The method of manufacture used pure natural silica grain instead of aluminum-doped inner silica grain. This natural silica grain contained roughly 8ppm aluminum.

Crucibles **A–C** and **P** were used in a 120-hour CZ-process, i.e., 120 hours at the chosen high temperature after melting of the silicon substrate. The results of these processes are shown in **TABLE 2**. Rosettes **52** were seen in the inner surface **62** and in the inner layer **16** of Crucible **A**. These rosettes had not spread so as to cover a high percentage of the inner surface **62** of Crucible **A**. Therefore, this

exemplary crucible preserved the smoothness of the inner surface 62 by inhibiting the spread of silica crystallization.

The rosettes seen on the inner surface 62 of Crucibles A and C were surrounded by cristobalite, both lateral to and medial to the rosette ring (FIGS. 18–  
5 19). The inner surface 62 inside the rosettes also had retained its smoothness.

Crucible B was similarly used in a 120-hour CZ-process. Rosettes formed in the inner layer 16 and had spread and merged so as to cover the majority of the inner surface 62. While little of the original surface remained, the inner surface 62 inside the rosettes nevertheless possessed a smooth surface. The silicon crystal ingot being  
10 pulled during the CZ-process was not compromised by the formation and spread of the rosettes in the inner layer 16 of this embodiment.

A fourth crucible was prepared according to the method of the present invention. Crucible D was made similarly to Crucible C, except that Crucible D was held at 1400–1600°C for one minute, and thereafter permitted to cool in the same  
15 manner as the crucibles discussed above, i.e., cooled for approximately five minutes.

Crucible D was subjected to a 120-hour CZ-process, after which the inner layer 16 was examined. The inner surface 62 was found to consist essentially of crystalline silica, with no rosette pattern evident.

The prior art Crucible P was used in a similar 120-hour CZ-process.  
20 However, at about 80 hours into the process, the nascent silicon ingot incurred a grain boundary flaw that disrupted its crystal structure. This flaw forced termination of the CZ-process and rendered the silicon crystal unsuitable for its intended use.

Examination of the inner surface of Crucible P revealed that it was nearly totally covered with rosettes, with very little of the virgin glassy surface remaining.

The surface within the rosette rings was of a rough texture and likely was the cause of the silicon crystal interference.

The crucible of the present invention provides improved dimensional stability. The inner layer also decreases dissolution of the silica glass into a silicon melt. Further, the inner layer of a crucible according to the present invention resists roughening during a CZ-process.

A person skilled in the art will be able to practice the present invention in view of the description present in this document, which is to be taken as a whole. Numerous details have been set forth in order to provide a more thorough understanding of the invention. In other instances, well-known features have not been described in detail in order not to obscure unnecessarily the invention.

While the invention has been disclosed in its preferred form, the specific embodiments thereof as disclosed and illustrated herein are not to be considered in a limiting sense. Indeed, it should be readily apparent to those skilled in the art in view of the present description that the invention can be modified in numerous ways. The inventor regards the subject matter of the invention to include all combinations and sub-combinations of the various elements, features, functions and/or properties disclosed herein.